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ULTRASONICS IN MEDICINE

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ABSTRACT

Our brief presentation of information on application of ultrasonics in medicine gives us reason to suppose that the further study of acoustical parameters of tissues, the development of dosimetric methods for determining the tissue absorption of ultrasound, and the perfection of ultrasonic therapeutic units will make ultrasonic treatments still more effective.

The improvement of ultrasonic diagnostic equipment, the development of better scanning systems, and the production of a narrow ultrasonic beam will equip the doctor with new reliable diagnostic methods.

It appears that ultrasonics will permit surgical operations to be performed without a single drop of blood. There is no doubt that in the not-too-distant future, the doctor and stomatologist, in conjunction with engineers, will also perfect the ultrasonic drill. Medical practice will make wide use of ultrasonic inhalators and sterilizers. The latter will be used both to sterilize surgical instruments and for hygienic purposes; they will enable us to make water fit for drinking without boiling.

There is no doubt that in the future ultrasonics will find ever-wider application in quite diverse fields of medicine.

TABLE OF CONTENTS

INTRODUCTION

In recent years, ultrasonics has found very extensive application in quite diverse fields of technology: sonar, industrial processing of metals, material defectoscopy, for studying the composition and properties of matter, for producing emulsions, etc. Ultrasonics is also employed in biology and medicine; this has been facilitated by successes in techniques of generating and receiving ultrasonic signals by studies of the way in which ultrasonic vibrations affect biological tissues, and by investigations into their acoustical parameters.

In this brochure the author briefly considers the nature of ultrasonic vibrations, the characteristics of its effects on living tissues and microorganisms, and applications of ultrasonics in various branches of medicine.

WHAT IS ULTRASONICS?

If any body is compelled to oscillate, oscillations will also appear in the medium surrounding the body. Propagation of the oscillations produces alternating compressions and rarefactions of this medium, which we call an elastic wave. The human ear is capable of perceiving and discriminating elastic waves, i.e., sound. Sound waves perceivable by the human have oscillation frequencies lying in the 16-20,000 hz range (1 hz is one oscillation per second; 1 khz = 10^3 hz; 1 Mhz = 10^6 hz). Oscillations with a frequency in excess of 20,000 hz cannot be perceived, and are called ultrasonic vibrations.

The piezoelectric or magnetostrictive effects are most frequently used to produce ultrasonic vibrations. Why is this so?

When certain crystals are in compression or in tension, electrical charges appear on their faces. This phenomenon is called the direct piezoelectric effect. The piezoelectric effect is reversible, i.e., the crystal will deform (become compressed or extended) if electrical charges are created at its faces. This phenomenon has come to be called inverse piezoelectric effect. The crystals possessing piezoelectrical properties include quartz, tourmaline, Rochelle salts, barium titanate, and many others.

If an alternating voltage from an oscillator is applied to a plate cut, for example, from a quartz crystal, the plate thickness will vary. The amplitude of the plate oscillations will be maximal when the oscillator frequency equals the plate resonant frequency. The thinner the plate, the higher its resonance. For a plate thickness of 2.87 mm, the resonant frequency will be 1 Mhz; for a thickness of 0.287 mm, the frequency will be 10 Mhz. Since for high frequencies, the plates would be too thin and fragile, quartz plates can only be used to generate ultrasonic signals up to 15 Mhz. A quartz plate can be used with equal success as an ultrasonic receiver. Barium titanate plates have recently been used in place of quartz plates.

The magnetostrictive effect consists in the following: ferromagnetic materials and their alloys change their linear dimensions in a magnetic field. Thus, for example, when an iron rod is introduced into a longitudinal magnetic field, the rod becomes elongated; the field has the opposite effect on a nickel rod: it becomes shorter. To compel the rod to change its dimensions (to vibrate), we place it within a coil carrying alternating current. The alternating magnetic field produced by the coil in this case

excites oscillations in the rod; their frequency is determined by the frequency of the current passing through the coil.

Magnetostrictive sources are widely employed to produce high-power signals in the 5-80 khz frequency range.

Like sound, ultrasonic signals generated by piezoelectric or magnetostrictive sources propagate in gases, liquids, and solids.

Ultrasonic waves resemble light waves in the way in which they propagate: just like light waves, they tend to propagate rectilinearly, and they can be focused into a thin beam or ray with the aid of a concave piezoelectric plate.

If an ultrasonic ray enters a medium whose acoustical characteristics differ from those of the medium within which the ray has been traveling, then like a light ray, the ultrasonic ray is refracted and partially reflected. The fractions of ultrasound refracted and reflected will depend on the density and elasticity of the two media, as well as on the angle at which the ray strikes the interface.

The most important parameters characterizing ultrasound include the following: the frequency f of the ultrasonic vibrations, the rate c at which the ultrasonic waves propagate, the intensity I of the ultrasound, the coefficient R, a parameter characterizing reflection of ultrasonic waves from the boundary of two media, and the absorption coefficient α.

Below we shall describe the foregoing basic parameters of ultrasound, as well as the phenomenon of cavitation, which arises when ultrasound acts on a liquid containing a dissolved gas. This information will make it simpler to explain the biological action of ultrasound.

When a generator of ultrasonic vibrations is turned on at a time t_0, the vibrations will be observed at a certain point a distance x away from the generator, not at time t_0, but after a delay Δt. The rate c at which ultrasound propagates equals the ratio of x to Δt; this is one important parameter. Thus for air at a temperature of 20°C, $c = 344$ m/sec; for water it is 1496 m/sec, and for such biological tissues as muscle, fat, etc., $c = 1490$-1610 m/sec; $c = 3380$ m/sec for bony tissue.

Since the frequency f of ultrasonic vibrations depends on the generator, while the rate c at which the ultrasonic waves propagate depends on the properties of the medium, the wavelength λ, which is the quotient obtained when we divide c by f, will be different for different media.

As it propagates in a medium, an ultrasonic wave naturally carries energy with it. The amount of energy transported by an ultrasonic wave in 1 sec through an area of 1 cm² located perpendicular to the line of wave propagation is called the intensity of the ultrasound; it is expressed in watt/cm². The intensity I of ultrasound depends both on the pressure P created by the ultrasonic source, and on the properties of the medium. For a plane

- 3 -

wave, the intensity I of ultrasound is directly proportional to the square of the amplitude of the pressure P^2, and inversely proportional to the product of twice the medium density ρ multiplied by the rate of ultrasound propagation in this medium, c.

An ultrasonic scale is used to measure the intensity of ultrasound. At one end of the scale beam there is a disk; to eliminate reflections and the attendant error, the surface of the disk is made in the form of a large number of cones.

To measure ultrasound intensity, the source is placed near a membrane, and the space between them is filled with water. The ultrasonic vibrations pass from the source through the water, the membrane, the water filling the scale housing, and then exert pressure on the disk.

The motion of the scale beam is transmitted through a lever to a pointer; the deviation of the pointer is greater the greater the intensity of the ultrasound. The scale is calibrated in watt/cm^2. The product $\rho \cdot c$ is called the specific acoustic impedance of the medium; in a certain sense, it can characterize the uniformity of the medium. If the specific acoustic impedance is the same at all points of the medium, then an ultrasonic wave will not be reflected during propagation. There will be partial reflection of ultrasonic energy at the boundary of two media having different acoustic impedances. The reflection coefficient R can be defined with the aid of the following formula:

$$R = \left(\frac{\rho_1 c_1 - \rho_2 c_2}{\rho_1 c_1 + \rho_2 c_2} \right)^2 \qquad (1)$$

If bony tissue with $\rho_2 c_2 = 6.2 \cdot 10^5$ g/cm$^2 \cdot$sec is placed in water, having $\rho_1 c_1 = 1.5 \cdot 10^5$ g/cm$^2 \cdot$sec, then the reflection coefficient R or the fraction of ultrasonic energy reflected from the bony tissue back into the water will be

$$R = \frac{6.2 \cdot 10^5 - 1.5 \cdot 10^5}{6.2 \cdot 10^5 + 1.5 \cdot 10^5} = 0.37.$$

Roughly the same amount of ultrasonic energy will be reflected from bone into soft tissues, since water and soft tissue have roughly the same acoustical impedance.

It follows from Formula 1 that more ultrasonic energy should be reflected the greater the difference between the acoustical impedances of the two media. Since air has an acoustical impedance that is less by almost a factor of 4 thousand than the acoustical impedance of water or soft tissue, there will be almost one-hundred per cent reflection of ultrasound at a water-air or soft tissue-air boundary, i.e., air chambers are a sort of acoustical shield, through which an ultrasonic wave cannot pass.

Any medium possesses internal friction, so that when an ultrasonic wave propagates in the medium, there will be absorption of ultrasonic energy, which turns into heat. The intensity of ultrasound diminishes with distance from the source in accordance with the law

where x is the distance from the source, α is the absorption coefficient, l is the base of natural logarithms, and I_0 is the ultrasound intensity at the source surface.

The absorption coefficient α depends on the properties of the medium, on the frequency of the ultrasonic vibrations, and is determined for certain liquids by the Stokes formula

$$\alpha = \frac{8\pi^2 \, \eta \cdot f^2}{3\rho \cdot c^3} \, , \tag{3}$$

where η is the viscosity coefficient for the medium. The absorption coefficient α is measured in cm^{-1}. The reciprocal of α is called the depth of ultrasound penetration; it indicates the distance at which the intensity of the ultrasound becomes equal to 14% of the initial value.

When an ultrasonic wave propagates in a liquid, under certain conditions the liquid may separate during a rarefaction phase, forming voids, which are filled with vapors of the liquid and gases dissolved in the liquid. At the next instant, during the compression phase, the voids collapse, as it were. This phenomenon has come to be called cavitation.

TABLE 1

1 Название среды	2 c, м/сек	3 ρ, плотность, г/см³
4 Вода	1526	1,000
5 Камерная влага	1534	1,012
6 Стекловидное тело	1534	0,992
7 Хрусталик	1647	1,136
8 Роговица	1639	—
9 Склера	1650	—

1) Name of medium; 2) c, m/sec; 3) ρ, density, g/cm³; 4) water; 5) aqueous humor; 6) vitreous humor; 7) crystalline lens; 8) cornea; 9) sclera.

Cavitation bubbles exert a destructive effect both on the medium and on a body in the medium: the polished surface of a metal immersed in a liquid acted on by ultrasound will become rough in the presence of cavitation.

The cavitation phenomenon takes place at high ultrasound intensities in liquids containing dissolved gases. It appears more readily at low ultrasonic-vibration frequencies than at high frequencies.

When ultrasound acts on animal cells, cavitation bubbles are not observed to appear within the cells themselves; this is explained by the high viscosity of cytoplasm.

TABLE 2

Название среды	α см$^{-1}$	$\frac{1}{\alpha}$ см
2 Вода	0,003	3000
3 Плазма крови	0,007	130
4 Кровь	0,02	50
5 Скелетные мышцы	0,2	5
6 Печень	0,17	6
7 Почки	0,22	5
8 Жировая ткань	0,13	8

1) Name of medium; 2) water; 3) blood plasma; 4) blood; 5) skeletal muscles; 6) liver; 7) kidneys; 8) fatty tissue.

The acoustical parameters of living tissues are of particular interest for ultrasonic diagnostics.

If we know the rate at which ultrasonic waves propagate in living tissues, the absorption and reflection coefficients, as well as the acoustical impedance, we can obtain diagnostic methods that are not only qualitative, but quantitative as well.

The rate c of ultrasonic-wave propagation has been determined many times in tissues and organs. Here no relationship has been noted between the rate c and the frequency f of the ultrasonic oscillations.

The ultrasonic method of determining formation of bone callosity in fractures can serve as an example of how a knowledge of the propagation rate of ultrasound in living tissues can be used. If we compare the rate of propagation of ultrasound through healthy bone and through fractured bone, we can form an opinion as to the rates of formation of bone callosity.

Ultrasound does not propagate at identical rates in different organism tissues. Table 1 gives the ultrasound propagation rate c in water and in eye tissues at 37°C; tissue densities are indicated.

Both the absorption coefficient α and the depth of ultrasound penetration $1/\alpha$ depend on the frequency f of the ultrasonic source.

If at $f_1 = 1$ Mhz, ultrasound penetrates to a depth of roughly 5 cm into muscle tissue, then at $f_2 = 100$ khz, the depth will be significantly greater, while at $f_3 = 100$ Mhz, the depth of penetration will be extremely small and the ultrasound will be absorbed in the topmost layers.

Table 2 shows the absorption coefficient α and the penetration depth $1/\alpha$ at a frequency of 1 Mhz.

It has been established that for several biological tissues (kidneys, liver, heart, etc.), the absorption coefficient α is a linear, rather than quadratic function of the frequency (see For-

mula 3). For bony tissue, however, a quadratic relationship has been observed between α and the frequency f.

All of this information must be taken into account when we investigate a given organ by means of ultrasound.

BIOLOGICAL ACTION OF ULTRASOUND

Biophysical measurements are extremely complex as compared with physical measurements, but biophysics is concerned with the most complex media, living tissues, which possess a whole series of specific peculiarities. The complexity of biophysical measurements is illustrated by the fact that, for example, in determining the acoustical parameters of precisely the same living tissues, different authors have arrived a notable diversity of results. Thus in studying the action of ultrasound on living tissue and in determining the acoustical parameters under normal and pathological conditions, as with any biophysical measurements, the maximum effect is attained when there is creative cooperation among physicists, doctors, and engineers.

Special units are used in the study of ultrasonic-wave action on living cells and small living objects; these units prevent the formation of reflections and standing waves in the liquid under study; they ensure that only the ultrasonic traveling waves act on the studied object.

Ultrasound intensities applied to living objects are classified as low (0-1.5 watts/cm^2), medium (1.5-3 watts/cm^2), and high (above 3 watts/cm^2).

Ultrasound exerts mechanical, thermal, and physicochemical effects on biological objects.

While an ultrasonic wave is passing through tissue, at each point in the tissue there will be an increase and decrease in pressure at the frequency of the ultrasonic oscillations. With medium ultrasound intensities, there will be "micromassage of the tissue," associated with the mechanical action of the ultrasound.

Living tissues can be heated by ultrasound first, at interspaces between two media differing in acoustical impedances owing to the difference in motion of particles in the two contacting media. Second, ultrasonic waves produce heat in connection with conversion of acoustical energy into thermal energy owing to absorption of ultrasound by the tissue.

As we can see from Formula 2, ultrasound intensity decreases upon passage through tissue. Naturally the acoustical energy does not vanish in this case, but is converted into thermal energy.

Absorption of ultrasound by tissue is caused, in the main,

by the internal friction or viscosity of the tissue.

When ultrasound is used for diagnostic purposes, the temperature rise in the investigated tissue can be neglected. In therapeutic applications, however, it is necessary to reckon with the possibility of heating and even overheating of the irradiated tissues.

Ultrasound has a physicochemical effect on living objects, for example, in irradiation of a liquid containing bacteria. If the ultrasound produces cavitation in the liquid, then the bacteria will be affected first by the pressure appearing when the gas bubbles in the cavitation void collapse and, second, by the resulting chemical reactions.

According to modern concepts, the cavitation phenomenon taking place in liquids does not occur under the same conditions in living tissue.

When low- and medium-intensity ultrasound acts on living cells, the variable ultrasonic pressure produces circulation of the protoplasm, and changes the permeability of the cell wall. It has been established that ultrasound of a particular intensity stimulates and accelerates exchange of matter between cells. It affects the activity of the enzyme systems localized in cell surface layers, affects the spatial configuration of submicrostructures within the cell, etc.

At high ultrasound intensities, morphological and functional changes take place in cells; these lead to irreversible damage. Ultrasound first disturbs and then completely halts metabolic processes. Next there is deformation of cell nuclei, destruction of the cell wall, and loss of protoplasm.

Living cells located in a liquid are subject to instantaneous destruction under the action of high-intensity ultrasonic waves. Only ultrasonic waves reaching a particular intensity, and capable of creating cavitation bubbles in the liquid, have this destructive effect.

As the intensity of the ultrasonic waves increases, more vigorous cavitation takes place; this results in the bactericidal effect of ultrasound. It has been established that it is more effective to increase ultrasound intensity than to increase the time over which it acts on the bacteria.

It has also been established that ultrasound acts selectively on different bacteria; it is assumed that this effect is produced by morphological peculiarities and functional states. The bactericidal effect of ultrasound will increase if the irradiated liquid is first saturated with gases. Even when there is no cavitation, ultrasonic waves are still observed to have a biological effect on living cells located in a liquid; this is explained by the acoustical motion of the biological particles.

Viruses and phages can be destroyed by the action of high-intensity ultrasound.

Several features characterize the action of ultrasound on an entire organism. The intensity of ultrasonic waves decreases as they penetrate the living organism; this is associated with absorption of the ultrasound by the medium within which it propagates.

In particular, the following fact is characteristic of living tissue: while in liquids, tripling of the ultrasound frequency will reduce the depth of penetration by a factor of nine, for the majority of tissues, frequency tripling will reduce penetration depth by roughly a factor of three.

An important property of ultrasound is its selective action on the tissues of an organism; this is explained by the nonuniform heating of individual tissues. It has been established that at ultrasonic frequencies (175-1000 khz), more heat forms at the interfaces of tissues and organs than within them. There is a particularly pronounced increase in temperature on a bone-soft tissue boundary. There are also data indicating that there is selective heating of peripheral nerves by ultrasound.

The effect of ultrasound on skin has received fairly detailed study. It is usually the skin that first receives the ultrasound and determines the upper bound of permissible intensity. Let us apply a source to the skin of the finger or hand. The ultrasonic oscillations traverse the tissues, and leave at the other side through the skin, entering the air. This may elevate the temperature of the skin opposite the point of application of the source, and may even damage this skin.

When there is an extremely thin layer of air between the source and the skin, the ultrasound may be totally reflected; thus neither the skin nor the tissue will be irradiated by the ultrasound. To eliminate the air layer we lubricate the skin, for example, with petrolatum oil, and only then apply the source to the skin.

At medium ultrasound intensities and with a "massaging" motion of the source, no changes in the skin or damage to it have been noted.

The effect of ultrasound on bony tissue is manifested primarily as the so-called boundary effect: heat is liberated at the soft tissue-bone interface.

There have been experimental observations of the effect of ultrasound on bone marrow, the animal reproductive system, internal organs (spleen, liver, kidneys), nerves, and the brain. These studies have become fundamental in ultrasonic therapy and surgery.

Despite the fact that ultrasonics has not been employed very long in medicine, it is now successfully employed in many areas of medicine.

Ultrasonics finds widest employment in therapy. Good results have been obtained in the diagnosis of illness with the aid of ultrasound. Ultasonics has been employed successfully in neurosur-

gery; it has begun to find application in stomatology as well. Ultrasound is used to sterilize and disperse fluids, as well as in inhalations.

Below we shall give a brief description, within the limitations of space, of applications of ultrasonics in the foregoing areas.

APPLICATIONS OF ULTRASONICS IN THERAPY

Application of ultrasonics for therapeutic purposes has proven very effective.

It has been established that the therapeutic action of ultrasound is based on the following: a) the mechanical action of the ultrasound, which produces varying ultrasonic pressure within tissues (micromassage); b) the thermal effect produced within tissues, and c) a complex physicochemical effect.

Numerous investigations have shown that ultrasonic irradiation of tissues is accompanied by hyperemia and analgesia (anesthetization). Owing to its specific action, for many illnesses ultrasonic therapy yields significantly better results than other methods of treatment.

Ultrasonic therapy is particularly effective in Bekhterev's disease, neuralgia, inflammation of the joints, neuritis, spondylitis, and other inflammatory processes.

It must be remembered that utilization of ultrasonic therapy is absolutely contraindicated in treatment of parenchymatous organs (liver, spleen, lungs, etc.), the heart, brain, etc.

The foregoing classification of ultrasonic intensity is fully applicable for ultrasonic physiotherapy; high ultrasonic intensities are never employed in therapy, however. The upper intensity limit for a therapeutic dose of ultrasound is 3 watts/cm^2.

The problem of the therapeutic ultrasonic dose is complicated by the following two factors. First, the ultrasonic field penetrating tissue during treatment will not be uniform. Second, the nonuniformity of the ultrasonic field itself is intensified by the inhomogeneity of the irradiated tissues. An organism contains various tissues separated by membranes. But these form interfaces, and are responsible for numerous reflections that influence the effectiveness of the ultrasonic field.

These characteristics of the ultrasonic field and of tissue must be considered in selecting both ultrasound intensity and irradiation time so as to produce the maximum medical effect.

Ultrasonic intensity is measured during therapeutic procedures by means of ultrasonic scales, while the procedure time is given by special timers that turn on the therapeutic ultrasonic equip-

ment for the time interval specified by the doctor.

Two basically different methods are employed in the practice of ultrasonic therapy: 1) direct irradiation of the affected region, and 2) indirect irradiation, in which the affected region is acted on through a reflex arc. Thus, for example, a medical effect is produced by irradiating appropriate sections of the spinal column, ganglia, and arteries.

With the first method of irradiation, the ultrasonic source is placed directly on the affected region. Here, as with the indirect method, the ultrasonic waves must penetrate the medium subject to irradiation. For this reason it is of primary concern to eliminate any air layer between source and skin. This is done either by immersing the body in water or by using a bonding liquid (petrolatum oil).
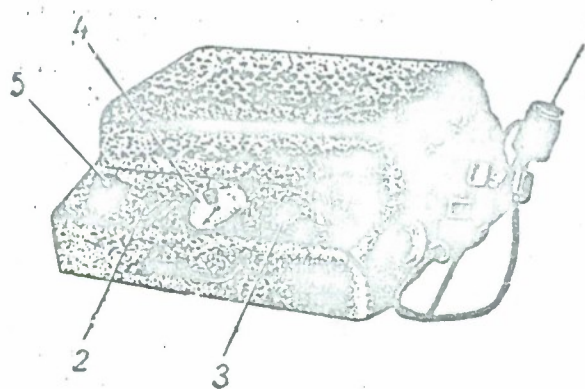
Fig. 1. Type UTP-1 ultrasonic therapy unit: 1) source; 2) mode switch (continuous, pulsed); 3) intensity regulator; 4) procedure timer; 5) monitoring instrument.

Ultrasonic therapeutic equipment is provided with sources differing in radiation area for both general and local irradiation. Radiation power can be controlled by means of appropriate fittings.

Large amounts of heat are liberated during ultrasonic therapy. One way of reducing the thermal effect is to use a massaging motion of the head. So-called pulse radiation has recently come into use. Here the pulse length and radiation intensity are selected so as not to cause great heating of tissue. Provision is made for a pause in operation of the equipment, during which the tissue cools.

Let us assume that the source transmits 100 pulses, each with a length of 1 m/sec. Here the tissue will be irradiated for 0.1 sec and cooled for 0.9 sec. Of course, under such conditions the tissue will only receive 0.1 times the energy it would have received from continuous radiation for the same time.

In some cases, for maximum medical effect, ultraviolet therapy

is combined with other types of physiotherapy (radiofrequency therapy, iontophoresis), or is used in conjunction with drugs.

The types UTS-1 and UTP-1 domestically produced ultrasonic therapy units were developed at the All-Union Scientific Research Institute for Medical Instrument Construction.

Domestic industry produces two types of ultrasonic therapy units: the stationary UTS-1 and the portable UTP-1.

The UTS-1 stationary unit can operate as either a continuous-signal or pulsed-signal generator. It generates ultrasonic oscillations at a frequency of 830 khz. The ultrasonic source has a working area of 10 cm^2, while the intensity reaches 2 watts/cm^2.

The UTP-1 portable ultrasonic therapeutic unit (Fig. 1) generates both continuous and pulsed ultrasonic signals. The ultrasonic source has a working area of 4 cm^2, with a maximum ultrasound power of 8 watts, the maximum intensity is 2 watts/cm^2.

The UTP-1 unit is provided with a procedure timer. The UTP-1 unit also includes an ultrasound-power meter (ultrasonic scale for checking the power controller). The device is light in weight (12 kg), so that it is possible to carry out procedures at the sickbed in a medical establishment or at home.

The relative simplicity of ultrasonic therapeutic units and their high treatment effectiveness has facilitated the broad-scale utilization of ultrasonics for treatment of many illnesses.

ULTRASONICS AND DIAGNOSIS OF ILLNESS

At present, ultrasonics is used for the following purposes: a) determining blood flow rate; b) determining degree of knitting of bone fractures; and c) echography.

Ultrasonic instrument for measuring blood flow rate. The measurement of blood flow rate is very important for the study of blood circulation, and for the diagnosis of arteriosclerosis and other diseases. Other than ultrasonics, there so far is no method employed that permits determination of blood flow rate without opening or preparation of a vessel.

The ultrasonic method of determining blood flow rate in arteries and veins is based on utilization of the Doppler effect; as it applies to the given case, this consists in the following. If ultrasonic waves with frequency f are directed through undamaged skin at a particular angle to the interface between a stationary medium (blood-vessel wall) and a medium moving at a rate U (the blood), then the ultrasonic receiver will pick up ultrasonic waves having a frequency that differs more from the frequency f the greater the rate of motion U of the blood.
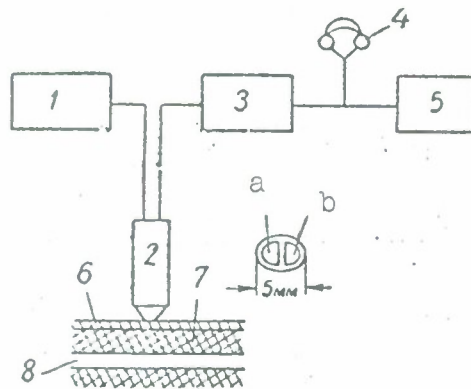

Fig. 2. Block diagram of instrument for measuring blood flow rate: 1) generator of high-frequency oscillations; 2) transducer consisting of source a and sensor, the receiving transducer b; 3) receiver; 4) telephone receiver; 5) recorder; 6) skin; 7) tissue; 8) investigated blood vessel.

Owing to the fact that the frequency of the reflected waves changes owing to the process of mixing of reflected and direct waves, it will be possible to detect and record noise with various frequency spectra at the receiver output. The nature of this noise will depend on the condition of the walls of the investigated vessel, its size, blood flow rate, etc. All other conditions being equal, the greater the blood flow rate, the higher will be the frequency of the noise at the receiver.

Figure 2 shows the block diagram of an ultrasonic device for recording blood flow rate. The ultrasonic-signal frequency f is taken as 5 Mhz in this case; the power of the high-frequency generator does not exceed 1-2 watts.

When the blood flow rate is measured, the transducer (2 in Fig. 2) is placed on the skin so that the ultrasonic beam is directed toward the blood vessel to be investigated.

The advantages of the ultrasonic method for determining blood flow rate in blood vessels include the following: a) the possibility of measuring blood flow rate without cutting the skin and opening the vessels; b) the possibility of recording the time variation in blood flow rate during an entire cycle of heart contraction; c) the linear relationship between the tone pitch or recorder deviation and the blood flow rate.

Instruments similar to the one described have found application in both physiological investigations and in clinical medicine.

Instrument for determining degree of bone-fracture knitting. The objective determination of the degree of bone-fracture knitting is based on measurement of the rate of ultrasound propagation along the bone as it passes through the fracture site. Ultrasonic waves propagate through intact bone at a rate of up to 380 m/sec. Clearly, this rate will be significantly lower where there is a fracture, while the rate of ultrasonic-wave propagation will increase as bone callosity forms.

This instrument (Fig. 3) consists of a generator of electrical pulse signals 1, an ultrasonic source 2, a sensor receiving the ultrasonic signals 3, a receiver 4 that picks up electrical signals from the sensor, amplifies them, and applies them to the cathode-ray tube 5.

The screen of the tube shows the pulse A delivered by the generator and the pulse B delivered by the receiver. The distance between pulses A and B on the screen of the cathode-ray tube is proportional to the time t that pulse B lags behind pulse A. If we know the distance l from the source to the sensor and time t, we will have no difficulty in determining the rate of ultrasound propagation ($c = l/t$).

For comparison, the same method is used to determine the rate of ultrasonic-wave propagation for a healthy extremity. Here the source and sensors are placed at the same points as for the affected extremity.
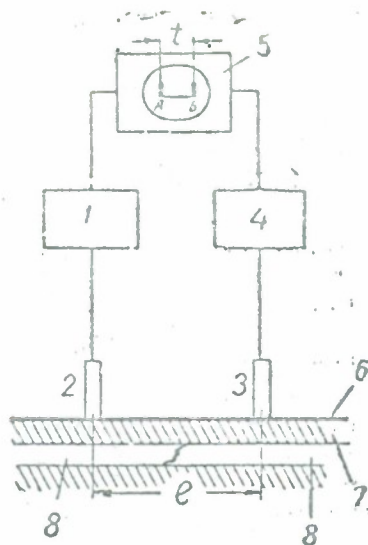
Fig. 3. Block diagram of instrument for determining degree of bone-fracture knitting: 1) high-frequency pulse generator; 2) source; 3) sensor-receiving transducer; 4) receiver; 5) electronic oscillograph; 6) skin; 7) tissue; 8) bone.

Echography. The echographic method is finding ever-greater application in medicine. It is a painless, harmless, and highly informative diagnostic technique.

Any piece of equipment for ultrasonic one-dimensional echography is similar in operating principle to a radar unit, except that an ultrasonic beam is used rather than electromagnetic energy in an ultrasonic locator.

As the very name implies, the echographic method is based on reception of ultrasonic waves reflected from tissue; these waves appear after an ultrasonic beam has been transmitted.

In echographic equipment, the source generates pulsed ultrasonic signals. The ultrasonic waves, moving in a given direction, reach the tissue to be investigated, are reflected from it and, passing through the transducer, are applied as an electrical signal to the receiving device of the equipment. The time interval between the pulse sent out by the generator and the pulse reflected from the tissue characterizes the distance to the point at which the ultrasonic wave was reflected.

An ultrasonic echographic unit consists of a power supply, electrical-pulse generator, ultrasonic-pulse source, piezoelectric transducer to convert the ultrasonic pulses reflected from the investigated tissue into electrical impulses, a receiver, and a cathode-ray tube. The same piezoelectric plate is frequently employed both to generate the ultrasonic impulses and to receive them.

Let us assume that an ultrasonic source I (Fig. 4a) is immersed in water, which is in contact with a body T; the latter
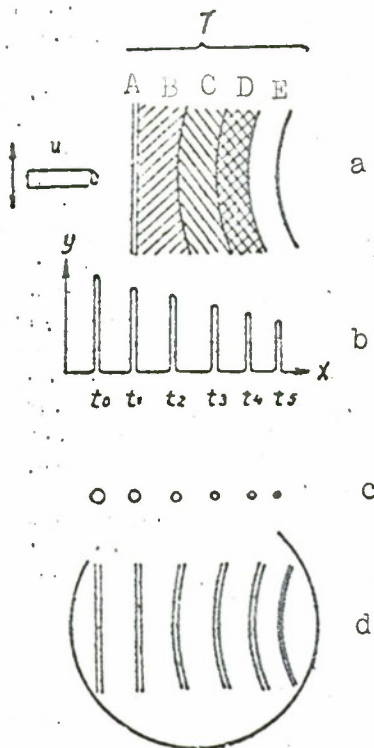
Fig. 4. Diagram illustrating operating principle of unit for ultrasonic echography.

consists of skin A and tissues B, C, and D, all of which differ among themselves in acoustical impedance.

If at time t_0 a short ultrasonic pulse is excited in the source I it will first be picked up by the receiver, and pulse I,a will appear on the screen of the cathode-ray tube; second, a highly directional beam of ultrasonic waves will appear; they pass through the water and reach the initial layer A, then B, etc. As the interfaces of layers A and B, B and C, etc., are reached, the partially reflected ultrasonic wave will be incident on the transducer and will appear at the receiver input.

The ultrasonic wave reflected from the water-layer A interface appears at the receiver input at time t_1, and pulse ll appears on the tube screen. Pulse lll from the interface of layers B and C arrives after a time t_2, etc.

As a result, on the screen of the cathode-ray tube, we can observe a whole series of pulses; they will have smaller amplitude the longer the path in tissue traversed by the ultrasonic pulse.

It should be remembered that only time is plotted along the X axis on the tube screen (Fig. 4b), and not the distance between the source I, the layer A, etc. If we wish to have distance rather than time represented along the X axis, we must know the rate at which ultrasound propagates in each layer.

It is possible to eliminate the Y-axis sweep of the cathode-ray beam, and to arrange things so that the electron trace is brighter the higher the intensity of the reflected pulse. In this case, the echogram will have the form shown in Fig. 4c.

If we wish to obtain a two-dimensional echogram, we must make source I (Fig. 4a) execute reciprocating motion in the plane of the figure (the direction of motion is shown by the arrow in this figure). A two-dimensional echogram will then appear on the screen of the tube (Fig. 4d).

While the one-dimensional echogram resembles a puncture by an ultrasonic "needle," which freely traverses uniform tissues and meets a certain resistance at the interface between two tissues, two-dimensional echography resembles a cut made by an ultrasonic "knife."

In one-dimensional echography, the source is applied to the body of the patient and held at the given point during the entire

investigation. Two-dimensional echography requires scanning, i.e., displacement of the sensor, as shown in Fig. 4a.

It is simplest to place the patient in a water bath, together with the source, which executes reciprocating motion. The examination can also be performed without a bath, however. Scanning can be accomplished as shown in Fig. 5a, where the source I is attached by a rod to a mechanism M that provides reciprocating motion in the direction indicated by the arrow. The source I is located in water contained in the polyethylene vessel N. The lower part of the vessel, lubricated with petroleum jelly, touches the skin K of the patient. As a result, there is good acoustical contact.
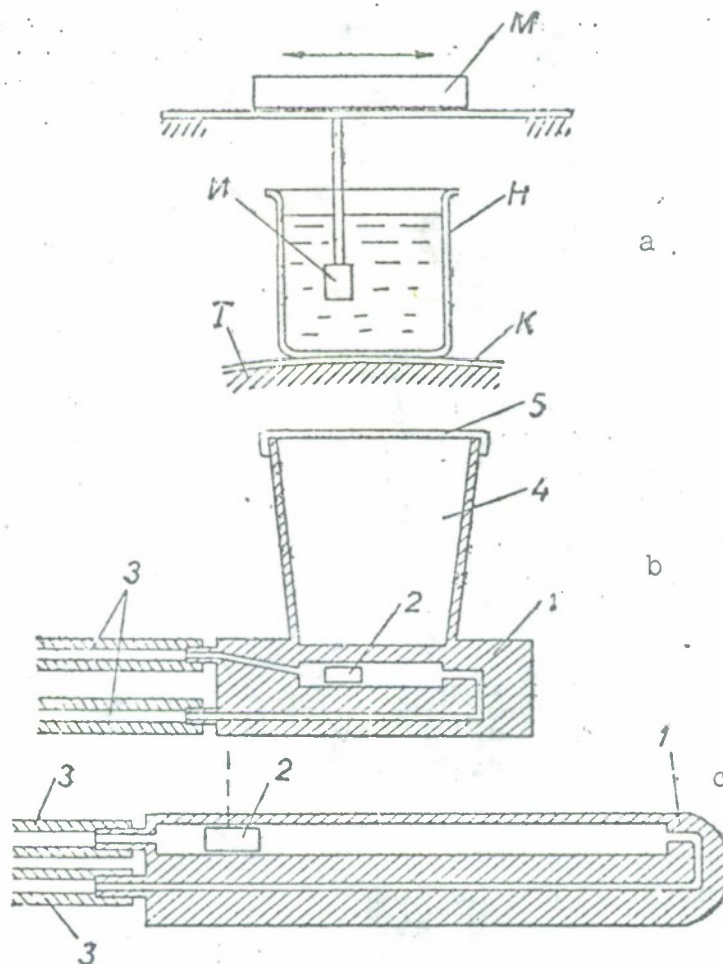
Fig. 5. Echo probes.

Such a scanning system can only be employed under stationary conditions, with the device mounted above the patient's bed.

Workers at the All-Union Scientific Research Institute for the Meat Industry have developed an original scanning system, some versions of which are shown in Fig. 5b and c. Reciprocating motion of the source is provided by a hydraulic drive mechanism that pumps water through hoses first in one direction and then in the

other.

Two types of probe were developed on this principle. One of them, shown in Fig. 5b, takes the form of a probe performing the same function as the one shown in Fig. 5a. This probe has a housing 1 made from plexiglas. The source 2 is forced to reciprocate by water delivered through rubber tubing 3. The ultrasonic wave traverses the plexiglas layer, the water filling space 4, the rubber membrane 5, the layer of petrolatum oil lubricating the outside of the membrane, the skin, and finally reaches the tissues to be investigated. It is then reflected from the tissues and returns to the source 2, which picks up the reflected waves during the pause following the ultrasonic pulse.

The hydraulically driven probe is much lighter and more convenient to operate than the probe that is attached to an electric motor and reduction gear for scanning purposes.

In addition, use of a hydraulic drive for scanning makes it possible to design a cavity probe (Fig. 5c) that is very small in diameter; this probe is introduced into a cavity, and makes it possible to obtain a two-dimensional echogram in the given position; when the probe is rotated in the cavity, an echogram in any direction can be obtained. It is an extremely complicated matter to design such a probe with a mechanical scanning system.

Echography has found application in many areas of diagnostics. Thus, for example, it has been used successfully to investigate the mechanical activity of the heart (ultrasonic cardiograph). Echography has been successfully employed in ophthalmology, neurosurgery and traumatology, obstetrics and gynecology, for diseases of organs of the abdominal cavity, etc.

The ultrasonic cardiograph takes the form of an instrument designed for one-dimensional echography with an optimal ultrasonic-signal frequency of 2.5 Mhz. Pulse length is 2-5 μsec, with a repetition frequency of 200 pulses/sec. The working portion of the source is 12 mm in diameter, roughly equal to the difference between two ribs.

To investigate the motion of the walls of the human heart, we apply the source to the petrolatum-oil-lubricated chest so that the ultrasonic beam, passing between the ribs, is incident on the investigated portion of the heart.

A one-dimensional echogram is produced on the screen of the cathode-ray tube; it shows, first, the generated pulse 1, then the pulse 2 reflected from the tissue between the ribs, and the pulses 3 from the various heart structures. The latter are displaced along the X axis (Fig. 6a) in synchronism with the heart activity.

Since the heart is partially surrounded by lung tissue, which vigorously reflects ultrasound, it is difficult to investigate the entire heart by such a method.

An ultrasonic cardiogram is recorded as follows: an objective O is used to throw an image of the pulses through slit Shch onto
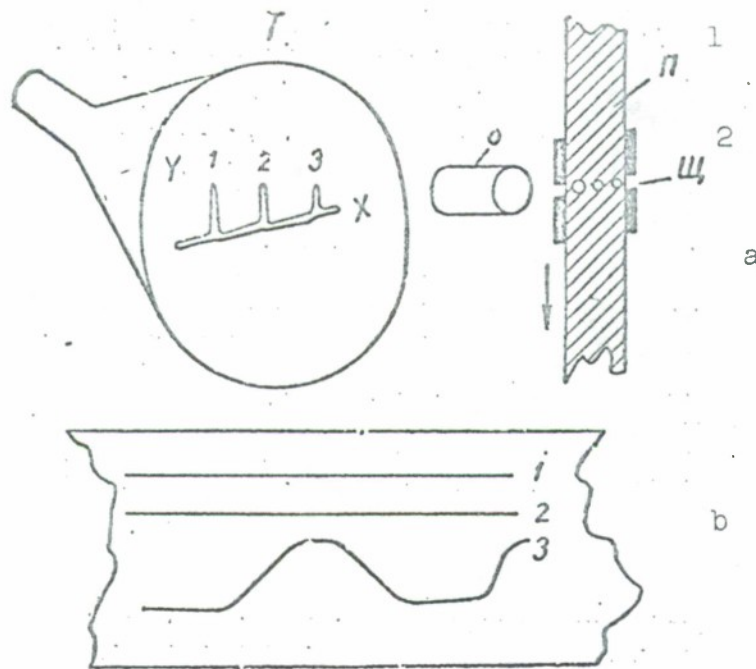
Fig. 6. Diagram showing recording of ultra-
sonic cardiogram: T) cathode-ray tube; O)
objective; Shch) slit; P) photographic film.
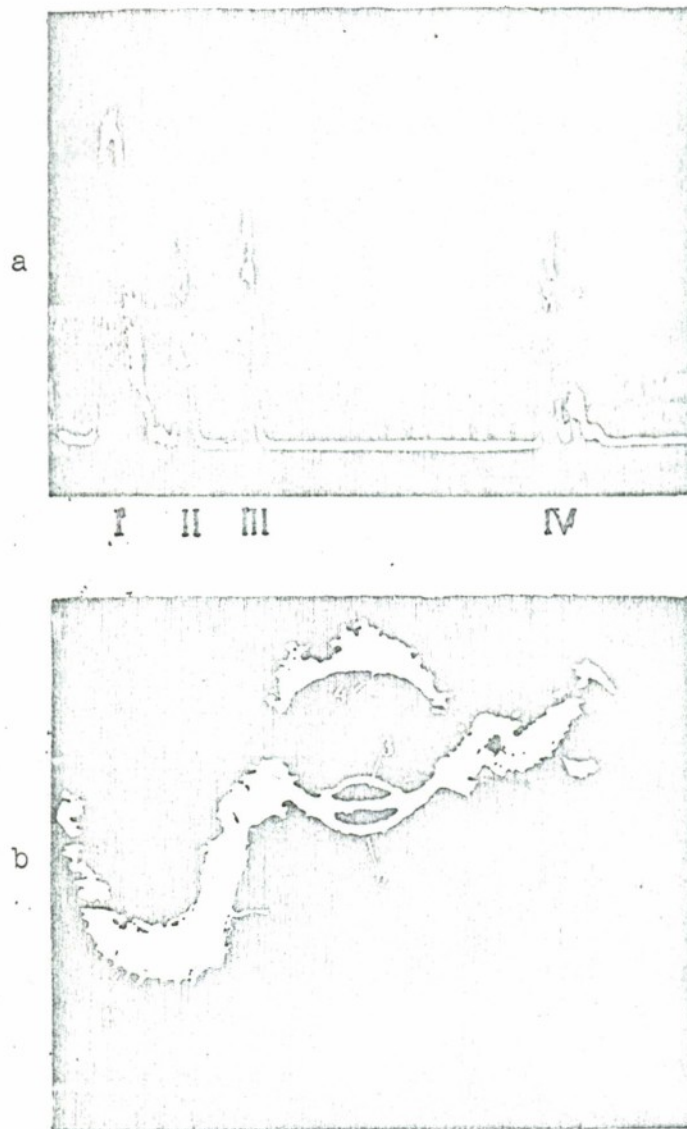1) P; 2) Shch.

the photographic film P. With stationary pulses, straight lines
will appear on the film (Fig. 6b). But since pulse 3, reflected
from the heart wall, moves along the X axis during heart activity,
the oscillogram will carry, in addition to the two stationary
lines 1 and 2, the curve 3; the latter reflects the motion of the
heart wall.

An electrocardiogram is ordinarily recorded on the oscillo-
gram together with the ultrasonic cardiogram.

The ultrasonic cardiograph has proven to be a very effective
diagnostic device; it makes it possible to form an opinion, for
example, as to indications and contraindications for heart opera-
tions, etc.

Ultrasonic echography has found wide application in eye
clinics as a very precise and harmless diagnostic method, having
no equals. It has proven uniquely effective where the most common,
visual method of examination, cannot be employed, for example,
when there is very slight clouding of the cornea or crystalline
lens.

The ultrasonic echographic method makes it possible to inves-
tigate the anatomical and optical elements of the eye, to detect
the location of hematomas, foreign bodies, and neoplasms in the
eye, as well as to trace the developmental dynamics of the latter.
Here diagnostic accuracy reaches 98%.

Fig. 7. One-dimensional echogram of eye a: I) pulse reflected from cornea; II, III) pulses reflected from front and rear walls of crystalline lens; IV) pulse reflected from back of eye. Two-dimensional echogram of eye, b: 1) nose; 2) cornea; 3) crystalline lens; 4) back of eye.

It is also possible to use two-dimensional echography for ophthalmologic purposes; this makes it possible to compare echograms, for example, for the healthy and sick eye (Fig. 7a and 7b).

One-dimensional ultrasonic echography has also been employed successfully to investigate the brain of a patient (echoencephalography). When the source is placed on the temples, for example, first on the left temple and then on the right, under normal conditions, the echograms (Fig. 8) will show the pulse II, reflected from the "center" structures of the brain (the so-called M-echo) to be exactly in the center, while if there are hematomas, neoplasms, etc., displacing the center structures, the M-echo will be

displaced and asymmetric.

Pulse I is the generator pulse, and pulse III the pulse reflected from the skull bone on the side opposite that to which the source has been applied.
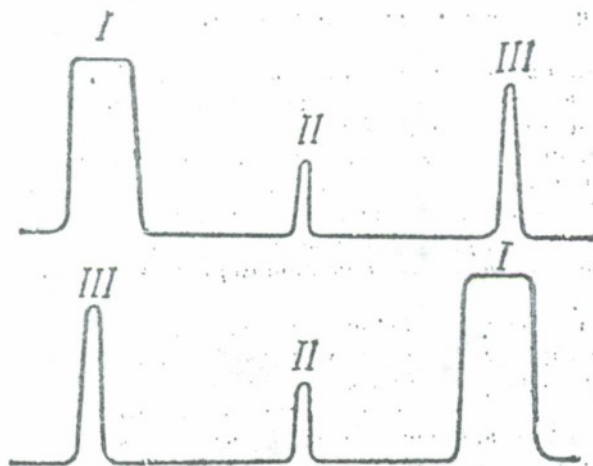

Fig. 8. Echoencephalograms.

Just as in the other cases of diagnostic use of ultrasonics, echoencephalography is completely harmless. Its use gives the neurosurgeon and traumatologist a powerful diagnostic weapon, permitting him to visualize on the tube screen and photograph changes in the patient's brain caused by trauma or neoplasm.

Ultrasonic echography has also found application in diagnosis of malignant tumors of the mammary gland (ultrasonic mammography), in recognition of diseases of the maxillary antrums, in investigating kidney and gall stones, tumors of the internal sexual organs (myomas of the uterus, cysts, etc.).

Echography has found diagnostic application in obstetrics. It permits determination of the position of the fetus, multiple-fetus pregnancy, and makes it possible to judge fetus developmental dynamics.

With the aid of a cavity sensor, ultrasonic echography makes it possible to establish the difference between a pregnancy and a fibromyoma of the uterus.

Special investigations have shown that ultrasonic echography is perfectly safe for both the mother and the fetus.

While a one-dimensional ultrasonic diagnostic unit is fairly simple, a two-dimensional unit is a fairly complex device.

As an example, we shall briefly describe the UZD-5 ultrasonic diagnostic unit developed by the All-Union Scientific Research Institute for the Meat Industry. The UZD-5 is designed for diagnosing tumors and certain other diseases in urology, gynecology, ob-

stetrics, etc., by the method of one- and two-dimensional echography.

As the investigated object becomes deeper, the signal amplitude decreases with one-dimensional echography; with two-dimensional echography, brightness drops off with increasing depth. Thus in the UZD-5, receiver sensitivity is made time-variable; this makes it possible to obtain pulses of similar amplitude, even though they are reflected from tissues located at different depths.

Figure 9 shows the block diagram of the UZD-5. The master oscillator generates pulses at a frequency of 1000 hz and a pulse length of 2-5 μsec. They synchronize the operation of the entire device. These pulses trigger the high-frequency oscillator connected to the ultrasonic piezoelectric transducer. The latter converts the high-frequency electrical impulses into ultrasonic pulses, and transmits them to the body of the patient. The ultrasonic pulses reflected from tissues are picked up by the same piezoelectric transducer, which converts them into electrical pulses, and applies them to the receiver input.

The receiver amplifies the high-frequency pulses, detects them, and then applies the signal to the indicator unit.
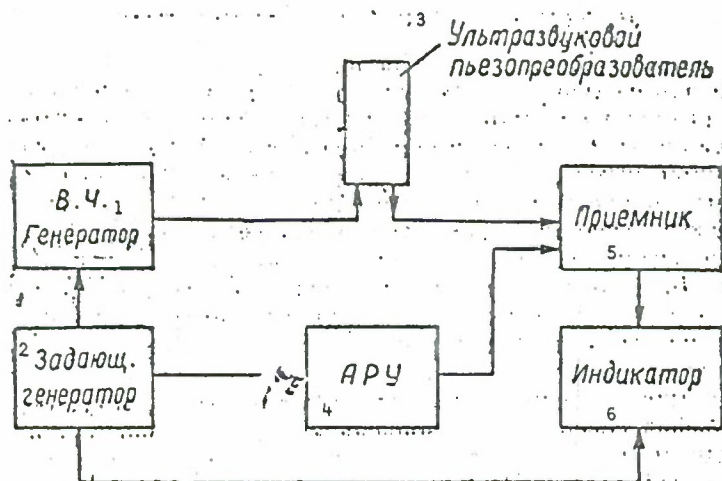

Fig. 9. Block diagram of UZD-5 ultrasonic diagnostic unit. 1) HF oscillator; 2) master oscillator; 3) ultrasonic piezoelectric transducer; 4) automatic gain control; 5) receiver; 6) indicator.

The indicator can be used with either one- or two-dimensional echography. Time pips appear on the screen of the indicator tube.

The UZD-5 is provided with an automatic gain control unit to compensate for attenuation of the ultrasound in the investigated tissues; the unit creates a voltage that varies receiver gain in accordance with a law that is close to the law governing attenuation of ultrasonic waves in tissue (deep-reflected pulses are amplified more than shallow-reflected pulses).

The automatic gain control unit makes it possible to obtain equal signal amplitudes at the output of the receiver for tissues located at different depths.

Both the high-frequency oscillator and the receiver can be tuned to the following frequencies: 0.88, 1.76, and 5.28 Mhz.

The successes of ultrasonic echography have led some to claim that this method is a serious competitor of x-ray techniques. This is unjustified. It is closer to the truth to say that both methods are complementary, and should be used to increase the quality of diagnosis.

APPLICATION OF ULTRASONICS IN OTHER AREAS OF MEDICINE

The surgical applications of ultrasonics are based on two different principles. In the first case, ultrasonic oscillations are imparted to the edge of the knife, so that tissue is cut bloodlessly, with less damage being done to the tissue, so that the wound heals considerably faster.

The treatment of certain diseases requires local necrotization of brain tissue in a rigidly defined site. To do this it is necessary to open the cranium, and to reach and cut the specified region of the brain. Naturally, such an operation is quite complicated.

Is it possible to perform this operation without opening the skull, by a bloodless method? It proves possible with the aid of ultrasonics.

If an ultrasonic source is applied to the skull, however, and the specified section of the brain is necrotized, the brain tissue along the entire path of the ultrasonic beam will also be necrotized.

This obstacle has been overcome as follows: several ultrasonic beams act on the patient's brain; they converge at the specified point. No individual ultrasonic beam has sufficient intensity to cause pathological changes in brain tissue, but their resultant intensity is sufficient to necrotize the tissue at the given point. The tissue and blood vessels surrounding this point are not harmed.

Obviously, the intensities of individual ultrasonic beams can add together at point O only if the ultrasonic waves from all sources arrive at this point in the same phase.

The volume of brain tissue to be destroyed is subject to regulation, and can be reduced from 2-3 mm^3 to a volume of 0.02 mm^3. There are two ways of solving the problem. In the first case, we use several ultrasonic sources (Fig. 10,I,1), which set up narrow beams of ultrasound, converging at the specified point within the brain. The ultrasonic beams pass through water 4, the bone of the cranium 5, brain tissue 6, and intersect at point O, where necrotization is to occur.

In the second case, only one ultrasonic source is employed (Fig. 10,II,1); ultrasonic beams are transmitted from this source

to a prism 2; leaving the prism, they strike the concave converging lenses 3. The beams are reflected from the lenses, and pass through the water 4, skull bone 5, and brain tissue 6, to be concentrated at the specified point 0.
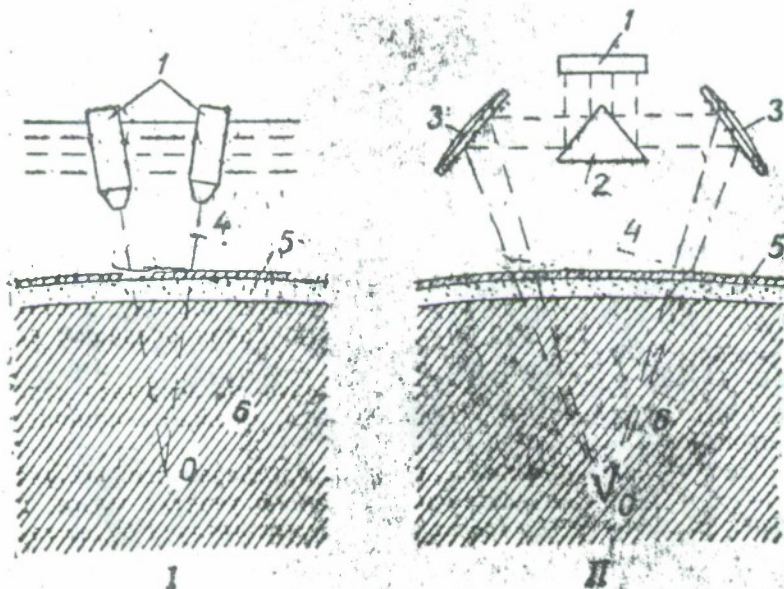

Fig. 10. Diagram explaining action of ultrasonic surgical device.

Stereotaxis equipment is used for precise setting and directing of the ultrasonic beams.

Treatment of Meniere's disease requires destruction of the vestibular receptors, and sometimes the cochlear receptor, all of which are located, as we know, in the inner ear; the other organs, including the auditory organ, must not be damaged. Doctors have also solved this problem with the aid of ultrasonics.

Surgical intervention precedes the ultrasonic action: the cells of the mammiform process and the threshold are cut to permit access to the semicircular canal. The sterile conical ultrasonic source is applied to the lateral semicircular canal, and after reliable acoustical contact has been established and the ultrasonic beam directed precisely (exactly toward the vestibular apparatus, and not toward the facial nerve or cochlear nerve), ultrasonic irradiation is carried out.

Here an ultrasound intensity of 9-10 watts/cm² is employed, with 12-15 watts/cm² in certain cases, but never more than 22 watts/cm².

The effect of the ultrasonic irradiation on the vestibular apparatus is checked by observing the nature of nystagmus (involuntary motion of the eye).

Ultrasonic units are also employed in stomatology. Thus, as

we know, removal of tartar from teeth is an operation that, while not painful, is quite unpleasant; ultrasonic equipment can be used successfully for this purpose.

Such a device, in particular, has been developed by the All-Union Scientific Research Institute for the Meat Industry; it consists of a generator of ultrasonic electrical signals with power supply, a magnetostrictive transducer to change the electrical oscillations into mechanical vibrations at a frequency of 25 khz, and a hydraulic system. The unit is provided with a set of attachments for the transducer, having tips of various shapes, so that access can be gained to any part of the oral cavity.

The operating principle of the unit is based on the phenomenon of cavitation, which takes place in the stream of water washing the tip; the latter vibrates at an ultrasonic frequency. The air bubbles formed during cavitation attack the tartar while they are collapsing, but do not damage the tooth enamel. The spent water is automatically removed from the oral cavity.

The unit permits bloodless and completely painless removal of tartar.

Attempts to create an ultrasonic drill have not as yet met with sufficient success. Such a "drill" has the same components as the unit for removing tartar, but an abrasive is fed in place of the water. Various shapes of tip fit over the magnetostrictive rod.

The tip, oscillating at ultrasonic frequency, is applied to the tooth together with a stream of water carrying the abrasive; this "drills" the tooth quite painlessly. A hole of any shape can be drilled in a tooth by this method.

The essential drawbacks of the ultrasonic drill include, first, the fact that the dentist cannot see the tooth surface on which he is working and, second, he cannot sense whether the tooth has been drilled out deeply enough.

Since high-speed dentists' drills are better in performance than ultrasonic drills, the latter have not yet found wide application in stomatology.

If liquid drugs are to be introduced through the lungs into the blood of a patient, they must be divided into fine particles, aerosols; this is done with the aid of an air jet (this is the operating principle of the atomizer). A compressor is required to supply air under moderate pressure to the inhalator. The use of ultrasound to produce aerosols is a simpler solution to the problem.

The ultrasonic source of such an inhalator breaks the liquid down into very fine particles, 3-5 microns; it operates noiselessly and reliably. Such ultrasonic inhalators are produced, for example, in the German Democratic Republic, and they have given a good account of themselves in practice.

We have already spoken of the possibility of destroying bac-

teria with the aid of ultrasound in the section on "Biological Action of Ultrasound." This means that ultrasonics can be used to sterilize and clean medical instruments when the desired effect can only be obtained in very complicated fashion by other methods, or is almost impossible to obtain in any other way.

Ultrasound is also employed to prepare biological specimens for electron-microscope study.

CONCLUSION

Our brief presentation of information on application of ul-
trasonics in medicine gives us reason to suppose that the further
study of acoustical parameters of tissues, the development of
dosimetric methods for determining the tissue absorption of ultra-
sound, and the perfection of ultrasonic therapeutic units will
make ultrasonic treatments still more effective.

The improvement of ultrasonic diagnostic equipment, the de-
velopment of better scanning systems, and the production of a nar-
row ultrasonic beam will equip the doctor with new reliable diag-
nostic methods.

It appears that ultrasonics will permit surgical operations
to be performed without a single drop of blood. There is no doubt
that in the not-too-distant future, the doctor and stomatologist,
in conjunction with engineers, will also perfect the ultrasonic
drill. Medical practice will make wide use of ultrasonic inhala-
tors and sterilizers. The latter will be used both to sterilize
surgical instruments and for hygienic purposes; they will enable
us to make water fit for drinking without boiling.

There is no doubt that in the future ultrasonics will find
ever-wider application in quite diverse fields of medicine.

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